Flammability Tests for Assessing Carpet Performance

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ABSTRACT: The potential of building materials to contribute to fire growth and spread has led to extensive regulatory control. Various and numerous small-scale tests are used to simulate and characterize flammability, flame spread and smoke production. Recently, the Fire Science and Technology Laboratory at CSIRO conducted an extensive research project into the performance in fire of flooring and floor coverings. Specifically, this paper focuses on an evaluation of four tests that could be used for controlling floor coverings, namely the Cone Calorimeter, the Flooring Radiant Panel (FRP), the LIFT Apparatus and the Early Fire Hazard Test (EFH). The reason behind the test selection was that the first three tests are internationally recognized while the fourth is a valuable, well-documented and validated Australian test that is referred to in the Building Code of Australia. EFH was originally developed to regulate wall lining materials but its use has been extended to regulate almost everything else, including floor coverings. Detailed test measurements in these apparatuses included ignition times in the Cone and EFH, critical heat flux in the Cone, FRP, LIFT and EFH, and rate of heat release and smoke yield in the Cone and EFH. Comparisons of similar parameters were made to investigate consistency of test results within the present regulatory requirements for floor coverings. In addition, prediction of flooring material behavior in each of these tests based on results from the rest of the tests was explored. Based on this comparison, the significance of each test with regard to providing information for flammability properties of relevance to control of floor coverings is established.

KEY WORDS: building material performance, floor coverings, flammability properties, test methods, fire.

INTRODUCTION

RECENTLY, THE FIRE Science and Technology Laboratory at CSIRO (FSTL) conducted an extensive research project into the performance

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in fire of flooring and floor coverings [1]. A previous CSIRO project had studied wall and ceiling linings [2]. The aim of the project was to recommend tests that provided suitable controls for regulating the use of floor coverings. The resulting recommendation was that to evaluate the hazard presented by floor coverings, two tests were needed, and the tests selected were the Cone Calorimeter [3] and the Flooring Radiant Panel (FRP). In addition to regulatory controls, the proposed tests can provide data for fire safety engineering.

The project focussed on an evaluation of four tests, the Cone Calorimeter, the Flooring Radiant Panel, the LIFT Apparatus and the Early Fire Hazard Test (EFH) [4]. The reason behind the test selection was that the first three tests are internationally recognized while the fourth is a valuable, well-documented and validated Australian test. EFH was originally developed to regulate wall lining materials but its use has been extended to regulate almost everything else, including floor coverings.

The selected tests measure various aspects of a material's potential for fire spread, fire growth and smoke generation. The Cone Calorimeter measures time to ignition, heat released as a function of time and smoke generated in terms of optical density. The FRP provides the critical heat flux at which horizontal spread stops. The LIFT Apparatus measures lateral flame spread and provides a critical heat flux that involves the same physics as the critical heat flux measured in the Flooring Radiant Panel. IMO has justifiably chosen to use the LIFT apparatus to regulate carpet applications in ships, acknowledging that the apparatus is not suitable for assessing the performance of melting materials. Because of its physical similarity to FRP, LIFT was not included in the experimental program. EFH results are reported in the form of indices that are related to ignition (Ignitability Index), upward fire spread (Spread of Flame Index), fire growth (Heat Evolved Index) and smoke production (Smoke Developed Index). As will be discussed later, EFH was developed to assess the performance of vertical wall linings.

It is difficult to correlate parameters (indices and properties) deduced from measurements in the selected tests. For example, the critical heat flux in the Cone is calculated from ignition time at different levels of irradiance, and is not assisted by radiation from a burning material. The critical heat flux of the FRP (that is defined as the heat flux at which flame spread stops) is primarily affected by the contribution of conductive heat from the flame front and to a lesser degree by the radiation from the flame. Nonetheless, such correlations (or the lack of them) can give us a clear indication of the usefulness of the tests in assessing hazard. This paper describes a number of comparisons to show why two tests are currently needed to characterize the behavior of

floor coverings, and the reasons for selecting the Cone Calorimeter and the FRP.

In this paper, the suitability of tests to measure vertical and horizontal flame spread is examined. Various measurements in the Cone Calorimeter with the Critical Heat Flux in the FRP are compared and ways of using data from the Cone Calorimeter to predict upward flame spread are examined. Methods of validating flame spread predictions from the FRP in large fire scenarios are also described and, finally, the usefulness of various smoke measurements is discussed.

VERTICAL AND HORIZONTAL FLAME SPREAD

The Early Fire Hazard Test (EFH) is a medium-scale test that is currently referred to in the Building Code of Australia (BCA) [5] to control the use of building linings (floors, walls and ceilings). A brief description of the test is included, as it might not be familiar to those outside Australia. A specimen of floor covering 600×450 mm is clamped in a vertical holder which faces a gas-fired radiant panel. The specimen holder is moved towards the radiant panel in a series of programmed steps over a period of 20 min, or until the specimen ignites, at which time the movement is stopped. Ignition is promoted by a gas pilot flame mounted 15 mm clear of the center of the exposed face of the specimen, triggering the decomposition products rather than the specimen itself. If ignition occurs, the radiation and smoke production of the specimen are monitored for 2 min (or more in certain cases) [2].

EFH is a medium-scale test for predicting flame spread on vertical surfaces. Under the current Australian Standard, data obtained can be used to derive indices that are generally suitable for application in deemed-to-satisfy regulations. However, the data is not suitable for use in fire engineering calculations, and the test method itself is not without problems. Its applicability in predicting performance of horizontal surfaces is not appropriate. In addition, certain materials, especially those that melt and drop away from the backing when exposed to heat, give low indices because of the lack of burning material at the point of most intense radiation. This does not reflect their behavior in a horizontal orientation, where molten material will stay in place until it is burnt. Other materials that have a high critical radiant flux and thus do not ignite easily can produce high flame spread indices in the EFH because these indices are calculated from measurements taken from the time of ignition, regardless of the incident radiant flux at which ignition occurs.

The Early Fire Hazard test was originally developed to overcome difficulties experienced in the use of BS476.7, Surface Spread of Flame Test [6],

for vertical flame spread. BS476.7 measures lateral flame spread on a specimen exposed to a decreasing radiant field. John Ferris of the Commonwealth Experimental Building Station (now part of CSIRO Fire Science and Technology Laboratory), where the test was developed, was aware that vertical flame spread was different from horizontal flame spread, and that BS476.7 did not take into account the heat release rate that was necessary to predict vertical spread. He developed the EFH to overcome these difficulties. In the EFH, the radiation levels as the panel approaches the burner simulate the radiation levels measured by Ferris in a corner test with dimensions $4.2\,m \times 3.7\,m \times 2.85\,m$ high, similar to the ASTM or ISO room corner test [7]. EFH became an Australian Standard and measurements in the form of indices for spread of flame and smoke developed were subsequently invoked in regulations to control the use, not only of vertical linings as originally intended but also of horizontal linings.

Figure 1 shows a comparison between Flame Spread as measured in accordance with BS 476:1953 and Time Interval (defined as the time from ignition to that for flames to reach a height corresponding to a 9 ft high ceiling, which is related to the Flame Spread Index in the current EFH standard) measured in the Vertical-spread-of-flame Apparatus (as EFH was then known). The comparison shows that there is little or no correlation between the two values. This early observation, taken from a paper written by Ferris in 1955 [7], showed clearly that the Vertical-spread-of-flame Apparatus is suitable for measuring upward flame spread for wall linings, but it cannot characterize horizontal flame spread. Unfortunately, the detailed work of Ferris was subsequently overlooked when the EFH was adopted for control of flame spread on horizontal surfaces.
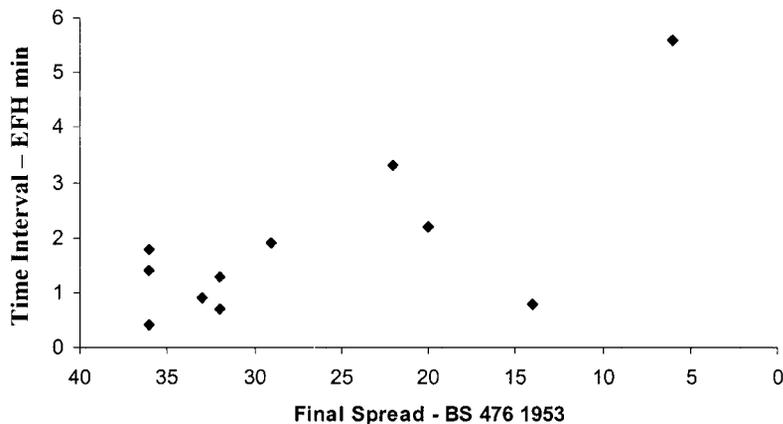

Figure 1. Time interval (EFH) vs. flame spread (BS 476:1953).

RELATION OF CONE CALORIMETER DATA
AND FRP CRITICAL HEAT FLUX

FRP measures the critical heat flux at which flame spread stops. The Cone measures time to ignition, heat release history and the critical heat flux needed to sustain burning. A discussion on the significance of critical heat flux in FRP is included in Appendix A.

During the course of the project, a number of materials were tested in the different apparatuses. A brief description of the floor covering materials tested is given below:

W2b – Wool carpet
 W5 – Wool carpet
 N9 – Highly flammable nylon carpet
RF1 – Smooth vinyl flooring
 P14 – Polypropylene carpet
N13 – Nylon carpet
N14 – Nylon carpet
N20 – Nylon carpet

Additional data from previous experiments is also used in some of the comparisons. Further details of the materials are given in the Project Report [1].

Attempts have been made to correlate Critical Radiant Flux in the FRP with various measurements in the Cone. Some of these attempts are illustrated in Figures 2–4.

In Figures 2 and 3, different aspects of heat release rate history obtained from the Cone are directly compared to values of Critical Radiant Flux (CRF) obtained from the FRP. Figure 2 looks at the maximum heat release rate while Figure 3 compares the average heat release rate over 300 s. The heat release rate in the cone is affected by the pyrolysis rate as well as the heat of combustion, whereas the CRF in the FRP is not affected by the pyrolysis rate. The CRF in the FRP is determined by the convective/conductive heat flux close to the flame front plus the external heat flux, but the convective/conductive heat flux does not depend on the pyrolyzing or heat release rate. Both proposed correlations (Figures 2 and 3) are empirical because they lack any physical reasoning. Both proposed selected values of heat release rate are arbitrary.

For example, Figure 2 shows that if the maximum heat release rate is used in the Cone, although there is some general trend, differentiation of the behavior of the material cannot be shown in horizontal situations. Thus, the maximum heat release rate is not a useful measure to predict horizontal flame spread. This agrees with the earlier findings of Tomann [8].
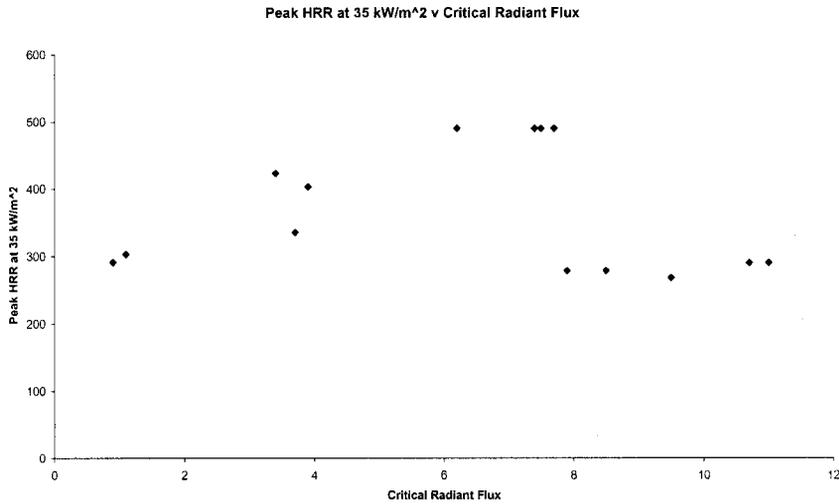
Peak HRR at 35 kW/m^2 v Critical Radiant Flux

Figure 2. *Peak HRR at 35 kW/m² vs. critical radiant flux.*

comparison of critical irradiant flux in FRP vs Heat Release average for 300s
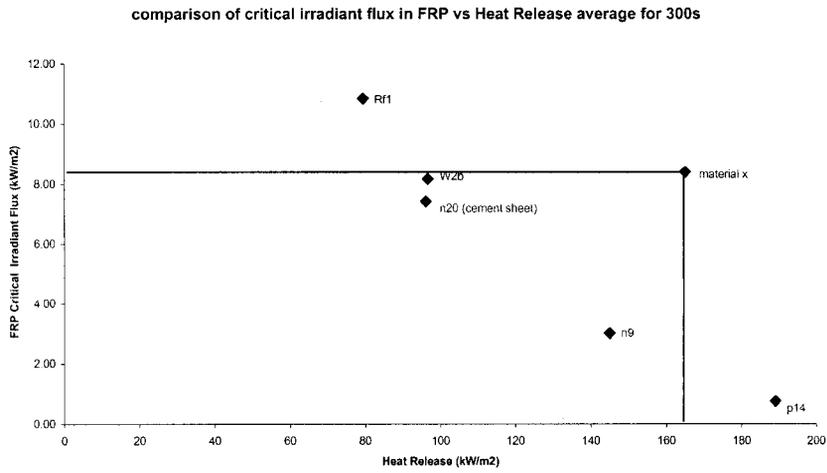

Figure 3. *Critical heat flux in FRP vs. average heat release over 300 s.*

At first glance and prior to inclusion of Material x, Figure 3 might appear to show an empirical correlation between the average heat release over 300 s and CRF in the FRP. However, this correlation is fortuitous as is shown by the inclusion of Material x [9], that was tested and added to Figure 3 after the completion of the project [1]. For this material, the average heat release rate over 300 s (at an imposed radiation level of 35 kW/m^2) is 165 kW/m^2,

Critical Heat Flux: Cone vs FRP
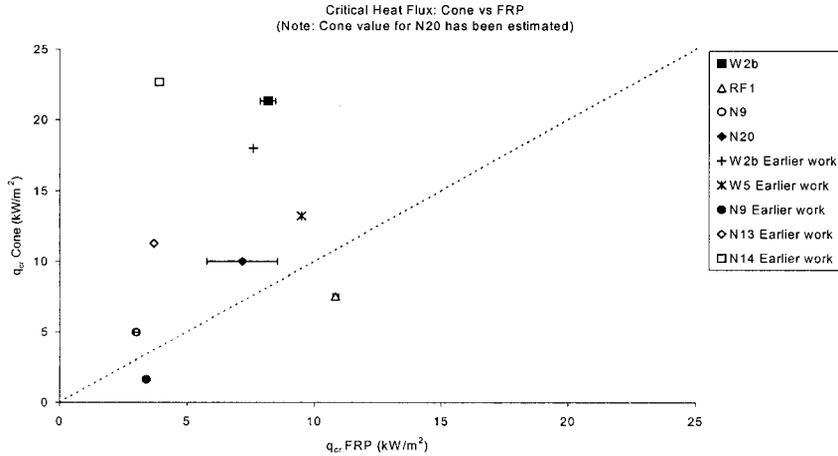(Note: Cone value for N20 has been estimated)

Figure 4. *Critical heat flux in cone vs. critical radiant flux in FRP.*

while the correlation suggested in Figure 3 by using the data from the other materials would indicate a value of about $85\,kW/m^2$ for a CRF in the FRP of $8.4\,kW/m^2$.

Finally, Figure 4 compares the critical heat flux in the Cone with the CRF in the FRP. It is obvious from the figure that there is no correlation. This result agrees with the following interpretation. In the Cone, pyrolysis is induced from the imposed heat flux only. The FRP characterizes opposed flow horizontal flame spread and pyrolysis is induced by both the external heat flux and convection/conduction from the flame at the front. It would, therefore, be expected that the "nominal" critical heat flux in the Cone would be higher than in the FRP.

PREDICTING UPWARD FLAME SPREAD USING CONE DATA

Based on the above discussions, it is apparent that to characterize the flammability of any material in a horizontal orientation, measurements are needed from both the Cone Calorimeter and the FRP. It can also be argued that the Cone can provide a suitable measure of smoke. Next, how data from the Cone can predict vertical flame spread is discussed, which applies to both wall linings and floor coverings used on stairs or in situations where flame spread is wind-assisted [10].

It has been shown in this work that measurement of lateral flame spread is insufficient to predict upward flame spread (see also [5]). For vertical surfaces, Heat Release Rate will affect the ability for fire to spread. Figure 5 shows maximum $HRR^2/t_{ignition}$ (both measured at $50\,kW/m^2$) against
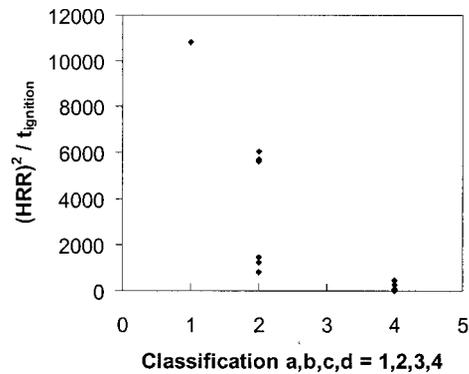
Figure 5. FSTL correlation using Japanese data.

classification based on time to flashover in the ISO Room Corner Test. This parameter determines a characteristic flame spread speed [11]. Basically, the numerator is a flame spread length scale and the denominator is the time of ignition and upward flame spread. The correlation is good. It is proposed that this parameter should be used to classify the hazard of floor coverings used on stairs. An alternative approach, that also shows that Cone data can be used to predict the ISO Room classification, has been proposed by Kokkala et al. [12].

VALIDATING FRP PREDICTIONS

The appendix to the ASTM Standard Test Method for Critical Radiant Flux [13] describes some experimental studies that investigated the appropriateness of the FRP as a control on floor linings. The experiments described show that, under conditions of moderate exposure (a crib or furniture fire spreading from an open door to a corridor), the extent of fire propagation from the source was inversely related to Critical Radiant Flux. However, for more severe exposures, only two of twelve floor coverings tested stopped burning at distances corresponding to their Critical Radiant Flux. In the other cases, it was apparent that the flux to the floor had been augmented by the heat release from the floor covering itself and probably from burning pyrolysis gases from the room fire that had migrated to the corridor. These effects will be influenced by the building geometry and ventilation.

Similar tests carried out in the FSTL full-scale corridor using a peak heat release rate of 2.5 MW in the adjacent room agree with the findings reported in ASTM E648 [14]. Under these conditions, for four of the
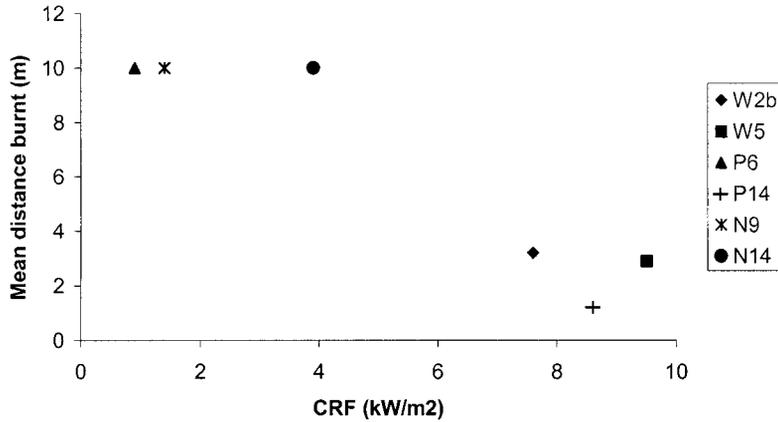
Figure 6. *Mean distance burnt in FSTL corridor vs. CRF.*

six floor coverings tested, the fire propagated to the end of the corridor (see Figure 6). The two carpets for which fire did not propagate to the end of the corridor had considerably lower heat release rates. From these tests, it cannot be determined whether floor coverings with Critical Heat Flux between 4 and 7.5 kW/m^2 would propagate to 10 m or not. An additional parameter to determine how far fire will spread for floor coverings with Critical Heat Flux within this range is the heat release rate from the floor covering. This parameter is measured in the Cone Calorimeter, as previously discussed.

SMOKE MEASUREMENTS

With the increasing use of fire retardants, materials with considerably reduced fire initiation and growth characteristics have become common. These materials tend to produce much more smoke and unburned pyrolysis products than the materials they have replaced. Thus, it is necessary to assess and regulate smoke (and other toxic gas) production as well as fire initiation and fire growth. In addition, in real fire situations, copious quantities of smoke can be produced in oxygen-reduced areas such as the hot layer in a room fire, where pyrolysis but no combustion occurs. It is important to consider smoke (and other gas) production for these situations.

The hazard caused by smoke (and other gas) production is related to the total production rate (kg/s) in a given situation. If the rate of fire growth is known and the products yield (kg/kg) is known, it is straightforward to calculate the production rate and the local product concentration.

Knowledge of lethal toxicity levels (for various products) provides criteria for fire safe design. ISO TC 92 follows this approach [15].

Only the Cone Calorimeter or a similar apparatus provides product (including smoke) yields for materials under over-ventilated burning conditions. It is known that the method used in the EFH apparatus for smoke characterization is qualitative and in some cases unreliable (it can predict less smoke hazard than actually exists). A method proposed for the FRP, but not adopted by ISO TC 92, is similarly lacking. An earlier study by Tomann [8] indicated that there is little correlation between smoke production in the Cone calorimeter and smoke production in the FRP.

In parallel to a complete engineering design, a simple approach is desirable to assess the smoke hazard for screening and regulatory purposes. Such an approach has been developed at FSTL [1].

It is based on the following considerations:

- The mass production rate of smoke (for example) is: $\dot{m}_s = \dot{m}'' Y_s A$ where $\dot{m}''$ is the burning rate per unit area, Y_s, is the smoke yield and A is the area involved in burning at a given time.
- The area involved in burning depends on how fast the fire grows. It is larger for wall linings for example than for carpets. For a wall or carpet of width W the area at time t is $A = WUt$ where U is the spread velocity.
- Both the vertical and horizontal velocities vary with external heat flux. The vertical spread velocity can be many times greater than the horizontal spread velocity. The vertical spread velocity depends also on the heat release rate.
- Neglecting the complications of spread velocities (these can be addressed by modeling), it has been suggested that an important discriminating parameter is the smoke mass production per unit area $\dot{m}_s/A = \dot{m}'' Y_s$. It is remarkable that this quantity is nearly the same both for ventilated burning conditions and pyrolysis in a nitrogen flow, for the same imposed heat flux.
- Notice that the mass pyrolysis rate is related to heat release rate by $\dot{m}'' = \mathrm{HRR}/\Delta H_c$ and the smoke yield, Y_s, is proportional to Specific Extinction Area (SEA) as measured in the Cone Calorimeter.
- Within an acceptable margin of classification reliability, the following simple parameter to provide a measure for smoke classification can be used:

$$\mathrm{HRR} \text{ (per unit area)} \times \mathrm{SEA}$$

Different limits should be set on this value for vertical and horizontal orientations because of the difference in spread rates. From Figures 7a and 7b, it can be observed that this parameter (which is proportional
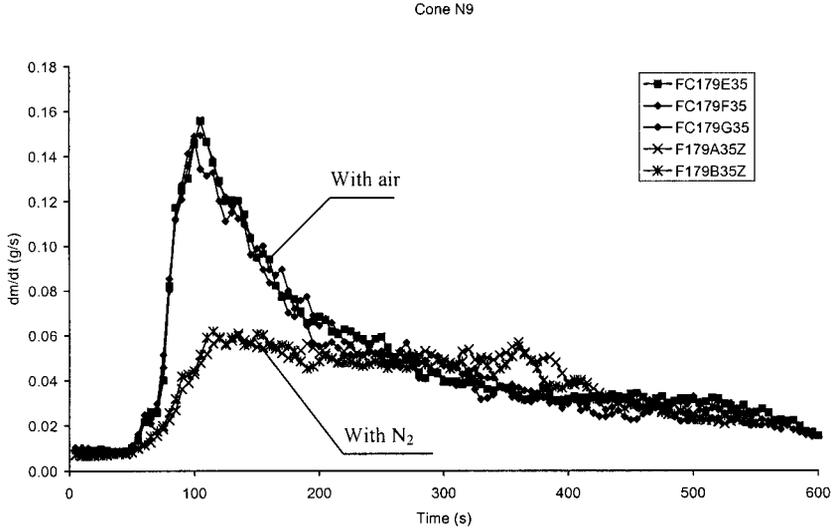
Cone N9

Figure 7a. *Mass loss rate vs. time for nylon carpet.*
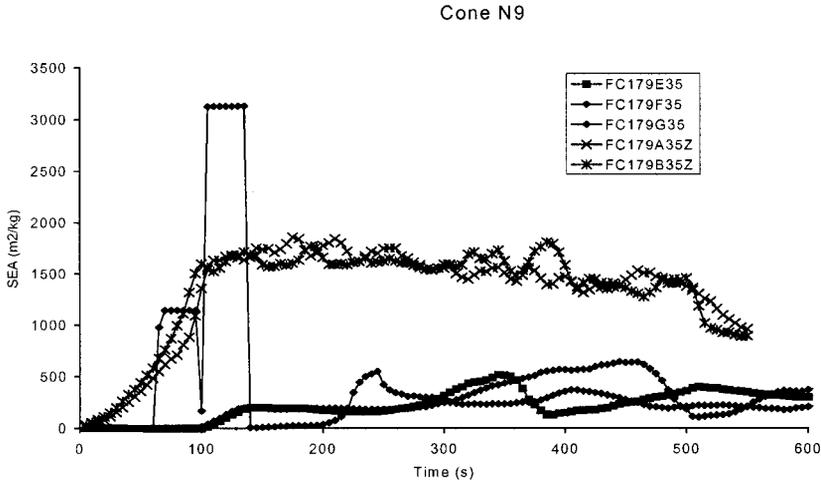
Cone N9

Figure 7b. *Specific extinction area vs. time for nylon carpet.*

to the smoke mass production per unit area) is of the same magnitude for the material whether it burns in ambient air and pyrolyzes in nitrogen. For example, pyrolysis conditions in nitrogen represent the decomposition conditions of materials in the upper hot layer of a developing room fire.

INCORPORATING DATA INTO FIRE ENGINEERING MODELS

Currently, most models used by fire engineers rely on either an αt^2 fire or the input of a design fire specified by the user in terms of heat release rate against time. Smoke generated is modeled using a constant value of optical density. The next generation of fire models will be much smarter at reproducing the pyrolysis process, and at modeling the spread of fire from object to object. While data in the form of indexes generated by tests such as the EFH can be used for approval purposes, the data generated by the recommended tests (Cone and FRP) will in addition provide direct input to fire engineering models. These models will require the following properties determined from the Cone:

1. critical heat flux for ignition in the Cone
2. k, ρ, C
3. Heat Release Rate
4. Charring properties
5. Smoke and toxic gas yields,

in addition to the critical heat flux to sustain horizontal flame spread measured in the FRP (as discussed before, this differs from the critical heat flux measured in the Cone). The proposed tests, therefore, not only give a realistic assessment of the hazard presented by floor coverings, but also allow the same test data to be used in sophisticated engineering calculations.

FSTL is already using such calculations to demonstrate the suitability of certain floor coverings in both specific and generic groups of buildings. Scenarios are chosen that illustrate the propensity of fire to spread, by the carpet alone and then taking other fire loads into account. If there is sufficient fuel for a flashover fire to develop without the carpet, will the carpet produce smoke or will fire spread to the carpet in an adjacent space? Scenarios are chosen that represent the likely fuel load and geometry of the building and, using data from both the FRP and the Cone Calorimeter, the influence of the carpet on the safety of those escaping the fire can be accurately predicted.

CONCLUSIONS

The main conclusions are:

• Cone Calorimeter data cannot be used to predict Critical Radiant Flux as measured in the Flooring Radiant Panel (see Figures 2–4).
• To characterize the flammability of any material, measurements are needed from both the Cone Calorimeter and the FRP.

- Maximum $HRR^2/t_{ignition}$ is a suitable parameter to classify the hazard of floor coverings used on stairs.
- Large-scale corridor tests [13,14] provide insufficient data to predict the performance of floor coverings under severe fire exposure. The heat release rate measured in the Cone Calorimeter is needed to predict this performance.
- It is necessary to consider smoke to predict the toxicity hazard posed by floor coverings. A suitable means of assessment using data from the Cone Calorimeter is

   HRR (per unit area) $\times$ SEA   (see "Smoke Measurements" above).

- The proposed tests provide data that is suitable for sophisticated fire engineering calculations as well as for the development of regulatory controls (see "Incorporating Data into Fire Engineering Models" above).

The Australian Building Codes Board recently proposed to adopt the use of FRP for flame spread for flooring, but the authors do not agree with the recommended use of the exhaust from FRP for smoke control. However, the work as summarized above has shown that both FRP and the Cone are needed to control flame spread, FRP for horizontal surfaces without wind resistance and the Cone for stairs and wind assisted situations. This conclusion is consistent with previous work [8,16,17]. Finally, only the Cone can give an appropriate measurement for smoke control.

ACKNOWLEDGEMENTS

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APPENDIX A

The Significance of Critical Heat Flux in the Flooring Radiant Panel

The FRP (ASTM version followed in Australia) requires a preheating period of 5 min before ignition by a line burner and that the imposed heat flux decreases away from the front of the sample as follows: $11 \, kW/m^2$ at 100 mm to $5 \, kW/m^2$ at 400 mm to $1.2 \, kW/m^2$ at 800 mm. Most of materials tested have a critical heat flux for ignition in the Cone Calorimeter that is greater than $5 \, kW/m^2$. So, even at steady conditions, the surface temperature of the sample will be less than its ignition temperature so that material cannot ignite.

Horizontal spread is assisted by gas conduction from the flames near the front in addition to the external heat flux (for the test condition in the FRP flame, radiation is not important because the flames are small). Moreover,

the external heat flux preheats the material until steady state conditions are established (external heat flux equal to surface radiation losses, and the material including the substrate is heated). This preheating will affect spread speed but not the condition that spread will stop or continue. At the front, the surface temperature jumps to the ignition temperature within a distance of a few millimeters [A1,A2].

The condition for (horizontal, downward and lateral) spreading is that the flame heat flux (by gas conduction near the front due to combustion) plus the external heat flux minus the critical ignition heat flux in the cone must be greater than zero. When these terms balance, the magnitude of the external heat flux is the critical heat flux for spreading. It is also noted that the gas conduction thermal length is fixed for normal gravity conditions and not affected by the spread velocity.

A simple relation for flame spread to stop is written as [A1,A2]:

$$\dot{q}''_{\text{ext}} = \dot{q}''_{\text{crit, cone}} - \frac{E}{\delta_f} \qquad \text{(A-1)}$$

Here, E is the (convective/conductive) energy from the flames and δ_f is the gaseous thermal diffusion length. This is constant for normal gravity conditions where gravity generated flow opposes the flame spread. These quantities are only slightly dependent on the surface temperature just ahead of the spreading front [A1,A2]. Therefore, the magnitude of the external heat flux in Equation (A-1), which is the critical heat flux for spread, does not depend on the preheating temperature. This was supported by exploratory experiments wherein the initial 5-min preheating period was bypassed and the sample was ignited just after exposure to the heating panel. The critical heat flux was the same as when the same material was tested according to the standard.

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